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Online on-board optimization of cutting parameter for energy efficient CNC milling

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Abstract

Energy efficiency is one of the main drivers for achieving sustainable manufacturing. Advances in machine tool design have reduced the energy consumption of such equipment, but still machine tools remain one of the most energy demanding equipment in a workshop. This study presents a novel approach aimed to improve the energy efficiency of machine tools through the online optimization of cutting conditions. The study is based on an industrial CNC controller with smart algorithms optimizing the cutting parameters to reduce the overall machining time while at the same time minimizing the peak energy consumption.

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1. Introduction

Sustainable use of resources has been the focus of research in many fields, including the manufacturing sector. Studies have focused on all aspects of sustainability including the social, environmental and economic aspects but mainly focusing on the latter. The industrial sector is one of the most energy demanding sectors accounting for a third of the total power consumption in Europe and is the most energy demanding sector [1]. Improvements in the energy efficiency of manufacturing equipment have started to reduce the impact of such equipment on the environment while at the same time ensuring a safe working environment. Machine tools, being the major power consumption source in workshop, have been the focus of a great amount of research. Sustainable machining has been a research subject with researchers focusing on the study of the energy consumption during machining, how it can be minimized and how to machine in a more environmentally conscious way. On the field of resource use optimization, there have been studies focusing on cutting condition optimization using online and offline systems.

This paper focuses on the creation of a system for online optimization of cutting conditions while taking into consideration the energy consumption during the cutting process.

The remainder of the paper is organized as follows: Section 2 presents the literature review in the subjects relevant to optimization and energy efficient machining. The optimization framework is presented in Section 3. Section 4 describes the mathematical models used in the optimization process followed by a case study in Section 5. Finally, Section 6 contains concluding remarks.

2. State of the Art

Energy efficiency in machining has been the subject of an increasing interest in industry as well as research. This paper describes the foundations of a system for promoting energy efficient machining through on-line manipulation of the cutting conditions by using cloud based information. This chapter focuses on the research in the fields of optimization in machining, energy consumption modeling and cloud systems.

Traditionally optimization in the machining sector is focused on reducing the overall machining time, reducing the machining cost and minimizing tool wear. Two are the main architectures used in optimization in machining are offline and online optimization. Offline systems use knowledge from

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previous parts and results of mathematical and simulation models to select the optimum cutting parameters for machining a specific geometry. This method allows for maximum manipulation of the toolpath, with the parameters tuned being, the cutting speed and feed, the depth and width of cut as well as the form of the toolpath itself. The optimization methods used in this type of systems include Genetic algorithms, Taguchi method and response surface methodology amongst others. These models are aimed to minimize the cutting forces during machining, avoid chatter regions and minimize cutting time and energy consumption [2-4].

In online systems the optimization of the parameters is realized as the cutting process is taking place. Sensors are used to give feedback to the decision making algorithm on the characteristics of the cutting process. The decision making algorithm evaluates the status of the cutting process and adjusts the cutting parameters accordingly. This is realized as the cutting process takes place. Usually the methods used in this area include Artificial Neural Networks and Fuzzy logic. The goal of such systems is usually the stabilization of cutting forces and chatter vibration avoidance [5-9].

In the field of energy efficient machining several researches have been presented focusing on the modeling of the energy consumption of machine tools according to their statuses [10-12]. According to [13] there are three different states that can be recognized during the machine tool operation, namely idle, startup and machining phases. In their research Rajemi et al. [14] measured the energy consumption during machining and presented that the power required for machining accounts for just over a third of the total energy consumption during machining. In Fig. 1 the phases of energy consumption described above are presented.

Moreover there have been many studies focusing on the impact of cutting conditions on the total energy consumption. These studies usually focus on finding the cutting conditions that minimize the cutting energy based on a series of experimental data [15-17].

Advances in Information Technology have enabled the use of more powerful controllers with very good networking capabilities. Also the area of Cloud Computing has been established lately in the IT area for providing computing services to clients. Similarly the area of Cloud Manufacturing has started to emerge in the area of manufacturing. Cloud Manufacturing describes the delivery of manufacturing services through a Cloud based environment [18]. This is achieved with the use of computing and manufacturing resources and is supported by the Internet of Things. Several researchers have explored this area and have proposed architectures that would help the implementation and adoption of such systems in SMEs [19-22]. One of the technologies proposed is the Event Driven Function Blocks (IEC 61499 [23]), technology that is currently used in automation technology and could be also implemented in CNC controllers. During operation, the Function Blocks receive commands through a series of event inputs that in turn trigger the internal algorithms of the structure through an execution control chart. The algorithms execute a series of calculations by consuming data from the input data ports and produce a series of data on the output ports as well as trigger output events. This technology can be used in order to directly drive CNC machines and bypass the G-code. The inherent networking capabilities of Function Blocks make them ideal for the use in a web based manufacturing environments.

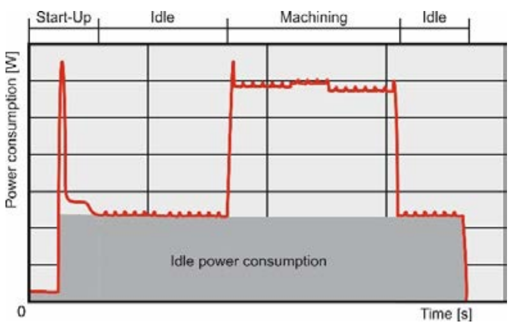

Fig. 1. Energy consumption during machining.

3. On-board optimization framework

This study presents an approach that uses an on-board optimization algorithm for adapting the cutting conditions during machining to select the optimal cutting conditions for machining. The implementation of the system was realized in Beckhoff's TwinCAT V3.1 [24] commercial industrial CNC controller. The controller is developed on Windows and provides a programming environment which is fully integrated with Visual Studio 2012, making it an ideal base for the development and deployment of the system. The controller comes with an emulator function which can be tuned to replicate the behavior of any milling machine. As it can be seen the proposed system uses Beckhoff's TwinCAT® as a base for all the modules included in the architecture. The modules are either embedded on the core of the controller or use a TCP/IP bus, embedded in the controller, for communication purposes. By using this modular approach the proposed system is able to run in, both simulation and real mode.

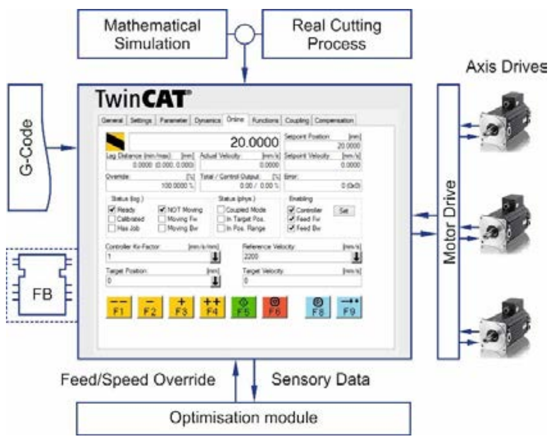

Fig. 2. On-board optimisation scheme

In simulation mode, mathematical models are used to provide the controller with the required input for the optimization process. This model is presented in a later stage of this paper. The model uses mathematical relations to accurately estimate the parameters needed for the optimization model and are able to provide data at high sampling rates.

In real mode the data needed for the optimization module are provided by embedded or external sensors and are processed online.

The controlling process starts with importing the machining commands to the controller software, realized by using a G-code file. After starting the execution of the machining code, the optimization module is initiated. This module retrieves parameters such as the position of the axes as well as the current feed and speed override. By using an Evolutionary Multi-Objective Model Predictive Control (EMO MPC) algorithm [25], the optimization module, provides the optimal cutting feed and speed back to the controller. This algorithm operates in a real-time mode and has to provide feedback before one controller cycle is finished. This is achieved by measuring the time that is required for a single generation of the optimizer (DMOEA in Fig 3.) and budgeting the remaining time before the next deadline making allowance for the time required by the decision maker.

In simulation mode the mathematical model is responsible for providing the sensory input, whereas the axis drives operation is simulated by the controller software. On the real mode the data comes from the sensors connected to the controller and the axis drives will actuate the physical system.

4. Milling Model

The simulation of cutting processes has been a research subject for many researchers [2]. The scope of these simulation models changes according to the results needed from them and include mathematical, analytical and solid based simulation models. The proposed framework requires a fast response simulation model for milling that can deliver data regarding the cutting forces and the power required to the controller software. For this reason a mathematical model was constructed. This model considers inserted cutters, but it could be extended to fluted cutting tools as well. The developed model calculates the cutting forces based on the equations developed by Kienzle and Victor [26] that use the non-deformed chip thickness to calculate three cutting force components.

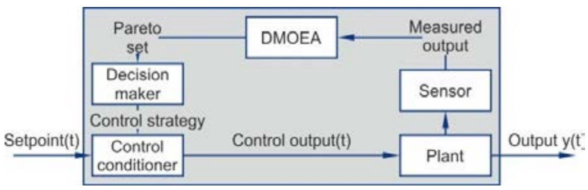

Fig. 3. Evolutionary multi-objective model predictive control

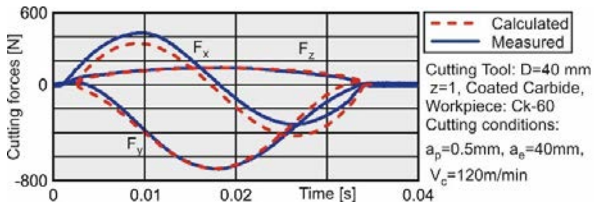

Fig. 4. Cutting force validation results

$$F_i(\varphi) = K_i \cdot b \cdot h^{1-m} \quad \forall i \in \{r, s, v\} \tag{1}$$

where K_r, K_s and K_v are the specific cutting resistance of the material, b is the width and h is thickness of the non-deformed chip.

In order to calculate the cutting forces for every cutting edge, using the above mentioned equation for a given angular position (φ) of the cutter the width and thickness of the non-deformed chip geometry must be calculated. This is realised by dividing the chip area into elementary areas in which the Kienzle and Victor equations can be applied. This process increases the accuracy of the model. After calculating the cutting forces for each elementary area of each cutting edge, they are added up and transformed in the common global coordinate system. The model was validated using experimental data from literature [27]. The comparison between the experimental and the calculated data is presented in Fig. 4

The calculated cutting forces are also used to estimate the cutting power required for machining. This estimation is realized using the following equation [2].

$$\text{Power}(\varphi) = Ft\,(\varphi) \cdot D \cdot \pi \cdot n/60 \quad \text{in [W]}, \tag{2}$$

where $F_t(\varphi)$ is the tangential component of the cutting force, D the cutter diameter and n is the programmed spindle speed.

The model described above is used to calculate the power consumption during machining and is one of the objectives being used in the optimization process, with the other objective being the minimization of time.

5. Application Scenario

In order to evaluate the functionality of the proposed approach a case study was constructed. A three axis milling machine configuration was used in order to evaluate the stability of the system. The proposed framework was deployed on a PC running the TwinCAT® environment. In the controller a three axis milling machine configuration was developed. The dynamic characteristics of each axis were selected such as to be near to what is found in modern milling machines [28]. After the development of the machine configuration, all the modules of the framework where linked to the controller and the system was ready for testing. The controller cycle time was set to 2ms, similar to what is found on modern CNC machines whereas the sampling of the physical system was executed every millisecond.

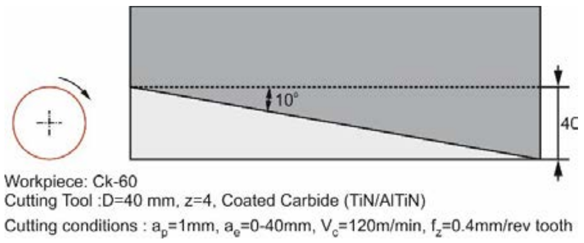

Fig. 5. Case study showing stock geometry and process parameters

The geometry selected for the case study as well as the initial process parameters for machining are presented in Fig. 5.

The material selected for the case study was CK60 carbon steel, which was used for the validation of the milling model, and the cutting tool geometry was identical to the validation case as well. The proposed framework, embedded on TwinCAT® controller environment was used emulate in a realistic manner the machining process. The results of the case study are presented in Fig 6, where the response of the system is highlighted.

As it can be seen the EMO MPC optimizer, which is implemented in Java with parts from the jMetal library [29], adapts the cutting feed (velocity) according to the changes in the geometry of the part in a smooth way without creating large values of acceleration and deceleration (see Fig. 6). After the initial acceleration of the drive, the speed is kept constantly high, since the material removed by the cutting process is limited. As the tool engages more in the machining of the part, the speed is gradually reduced to allow for lower cutting forces and as a result lower power consumption and wear. The cutting feed is further decreased when the cutter reaches approximately the position X=115, since from that point onwards more than one cutting edge is employed in the cutting process. After that point the cutting tool reaches a power plateau and travels at a fixed speed until the exit phase where the tool is speeded up, since the cutting forces and the cutting power are reduced to allow for decreased air cut time.

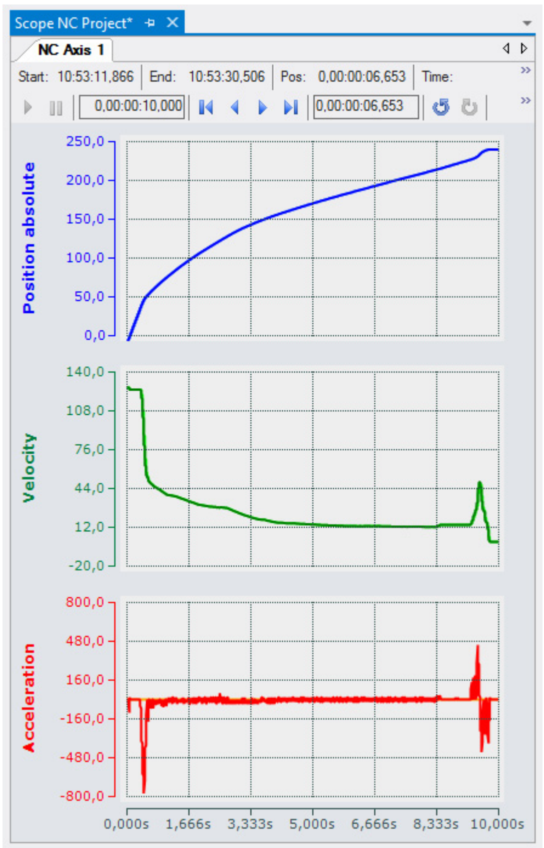

Fig. 6. Optimal control strategy (screenshot from the TwinCAT® control process environment; position x of the cutting head in [mm], velocity in [mm/s] and acceleration in [mm/s2])

Fig. 6 presents the power consumption of the main spindle for constant feed and optimized feed. The proposed strategy minimizes the air-cut time and reduces the overall machining time. The system also stabilizes the cutting forces allowing reduced power consumption peak and average power consumption.

The EMO MPC optimizer achieves a significant reduction in cutting time compared to the constant feed rate solution. In this example the cutting time is reduced by 17%. In addition to the overall machining time reduction there are a series of additional benefits that are achieved with this approach. Since the cutting forces are stabilized and peaks in the cutting forces are avoided, the tool wear is reduced and the tool life is maximized. Moreover, the reduction of peak and average power consumption is achieved. The reduction of the overall machining time brings an additional reduction in the total power required by the machine, since the subsystems of the machine have to operate for less time. As discussed previously the machining power accounts for a third of the total energy consumption of the machine and thus a reduction in the total machining time has a considerable effect in the on the total energy consumption. The reduced prolonged tool life coupled with the energy savings achieved by the stabilization of the cutting forces and the reduction of machining time can lead into a more sustainable solution in the machining sector.

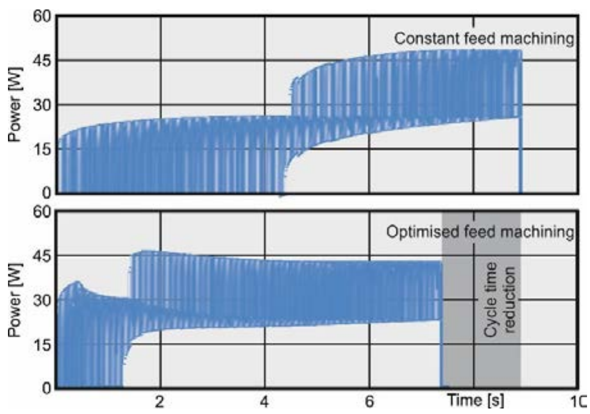

Fig. 7. Initial and optimized required power

6. Conclusions

Optimization of cutting conditions in machining is a critical aspect that has been investigated by many researchers, with the environmental impact of machining processes being the focus of research lately. This paper presented an architecture for on-board online optimization of the cutting conditions during machining while taking into consideration the above mentioned aspects. The proposed solution was based on an industrial controller TwinCAT® and was tested using realistic CNC parameter settings. A case study was constructed for highlighting the functionality and robustness of the proposed methodology. Through the case study the flexibility of the proposed approach was presented showing that it can cope with the real-time constraints of real world controllers and adapt the cutting conditions offering optimal machining parameters. The proposed framework achieved the minimization of cutting time while – at the same time – was able to keep the power consumption at a minimum. The proposed approach can enable controllers to automatically adapt the cutting parameters in a dynamic and easy to implement way. The evaluation of potential intervention is realize with respect to environmental criteria, energy consumption, and can be implemented without additional sensors by using the pre-installed sensors on modern milling machines. Since the module runs in an onboard manner there is no need for additional PC and external wiring, making it easier to use in a real manufacturing environments. The modularity of the proposed approach also makes it ideal for the use in a web based environment, through which it could retrieve information regarding feeds and speeds for the cutting tools as well as inform the user about the cutting process characteristics.

With regards to future work on this module, these include the design of a more complex case study as well as the testing of the framework on physical machine tools.

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